Orbit-Deflecting Magnet Errors in the SNS Ring: Effects and Correction

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Overview: 3 Types of Orbit-Deflecting Errors

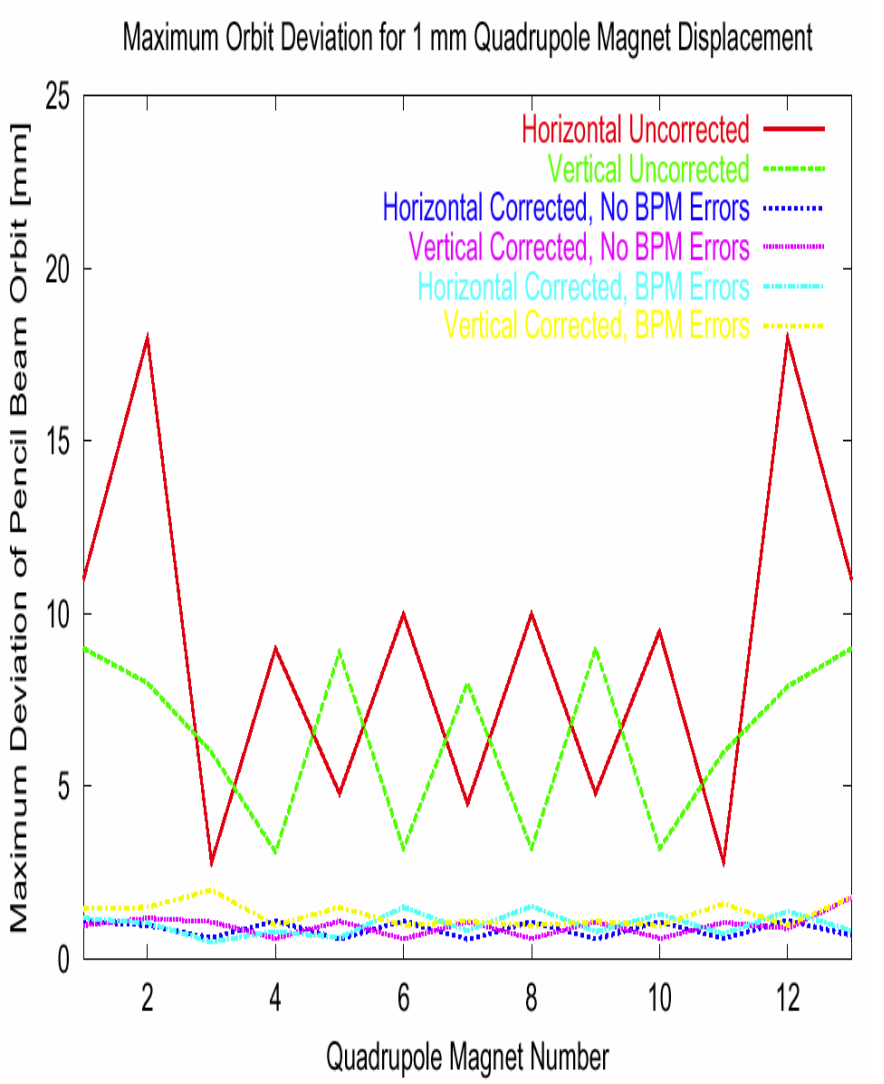
- Study 3 types of orbit-deflecting errors using ORBIT code:
  - Quadrupole displacements errors
  - Dipole displacement errors
  - Dipole field errors

- Focus on orbit deflection and losses:
  - Orbit deflection studied using “standard pencil beam”
    - Initial coordinates at injection point on desired closed orbit
  - Losses studied for full 1.44 MW injection scenario
    - $1.5*10^{14}$ protons at 1 GeV

- Carry out error correction by setting dipole corrector strengths to minimize BPM signals:
  - 24 horizontal, 28 vertical BPMs - with or without random signal errors
  - 24 horizontal, 28 vertical dipole corrector strengths
  - Least squares:
    - Minimize sum of squares of BPM signals (beam dipole moments)
    - Use standard pencil beam

Quadrupole Displacement Errors: 1 mm Single Quadrupole Displacement

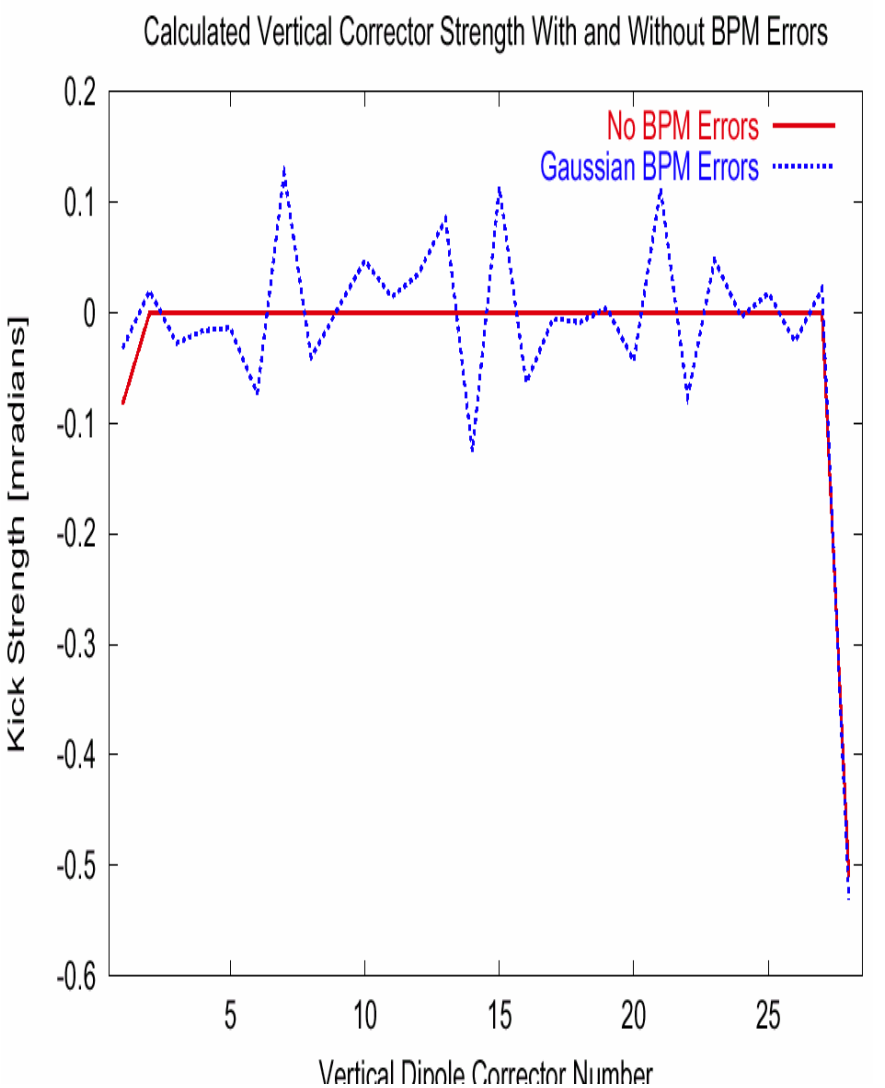
- **Displace individual quadrupoles by 1 mm:**
  - **Orbit deviations periodic with ring superperiodicity**
  - **Large horizontal orbit deviations at doublet focusing quadrupoles**
- **Error correction by BPM minimization:**
  - **Exact BPM signals**
  - **BPM signal errors**
    - **Random truncated Gaussian distribution:**
      - **Sigma = 0.5 mm**
      - **Cutoff = 1.0 mm**



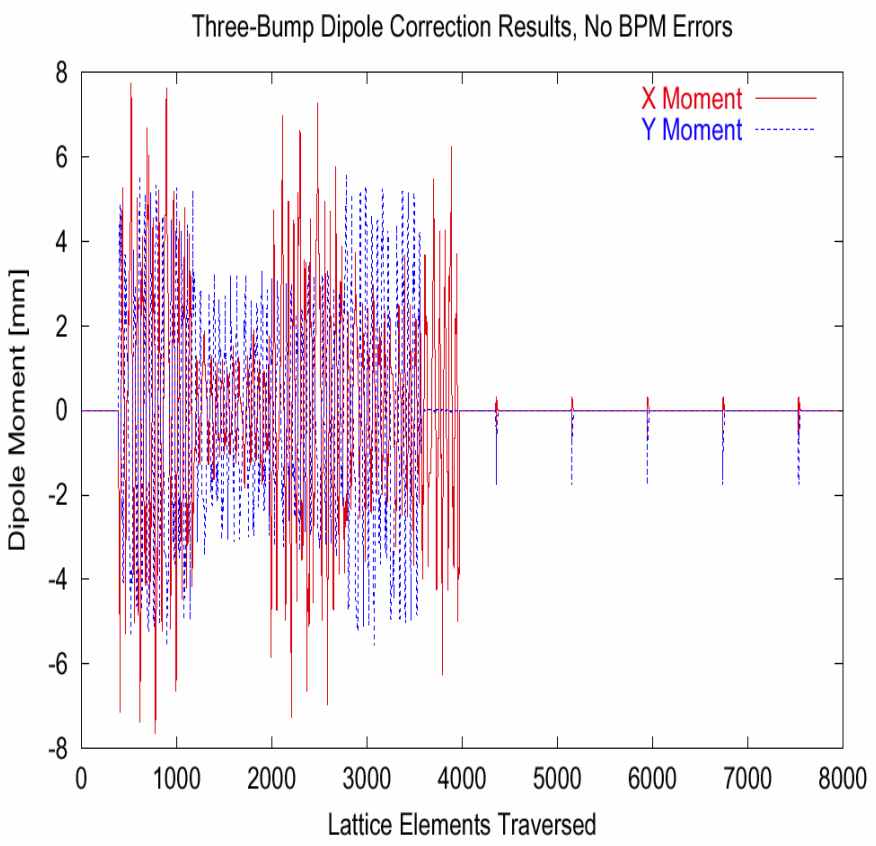
1 mm Single Quadrupole Displacement: Dipole Corrector Strengths

- **With exact BPM signals:**
  - **Least squares optimizer chooses 3 bump scheme**
  - **Only 2 adjacent dipole corrector magnets activated**
  - **Orbit deviation is confined to region between displaced magnet and its 2 adjacent dipole correctors**
  - **This is also true for dipole displacement and field errors**

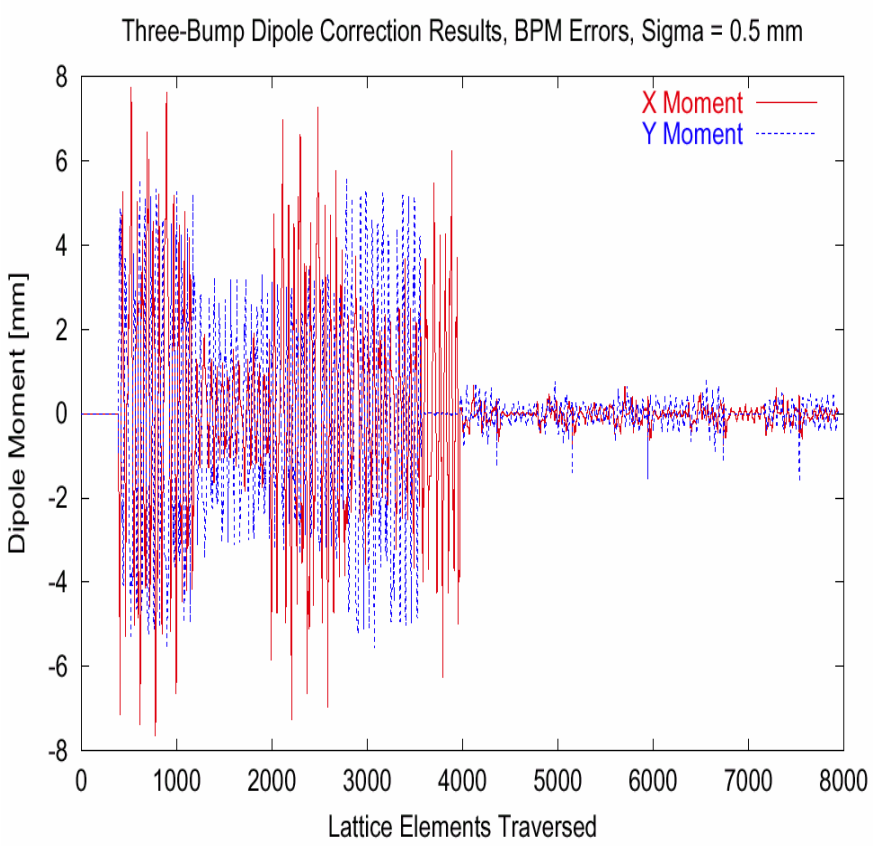
- **BPM signal errors:**
  - **Minimization with errors activates all dipole corrector nodes, most at a low level**
  - **Orbit deviation mostly confined to "3 bump region" but some noise everywhere**



1 mm Single Quadrupole Displacement: Dipole Corrected Pencil Beam



Exact BPM Signals

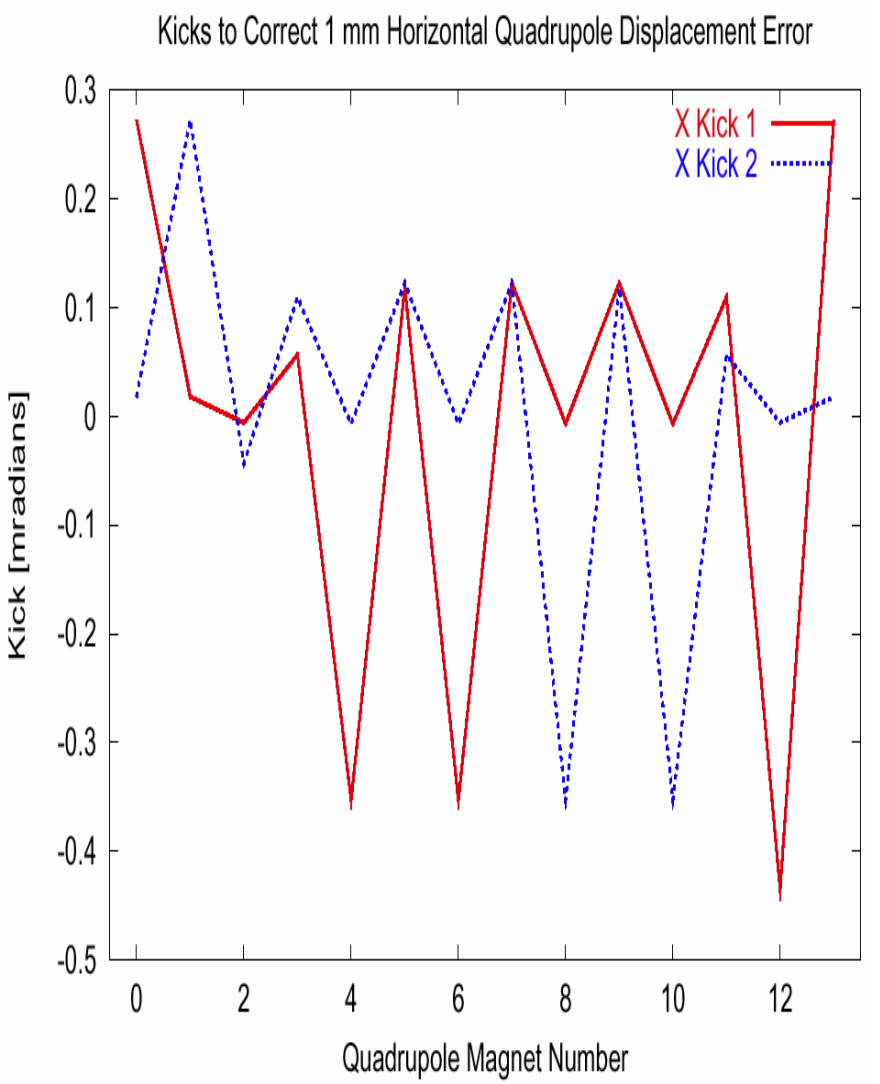


BPM Signal Errors

5 Turns Uncorrected Followed by 5 Turns Corrected

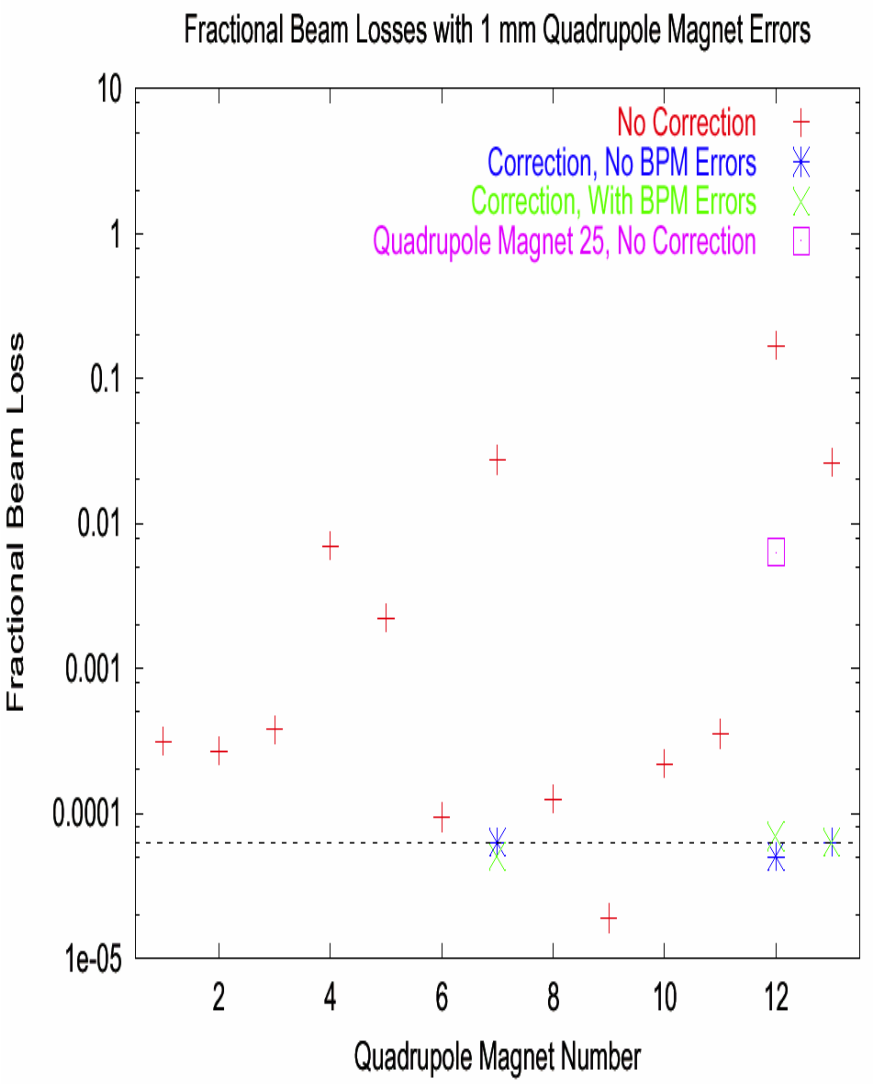
1 mm Single Quadrupole Displacement: Dipole Correction Kicks

- **Optimizer selects 3 bump method:**
  - **2 adjacent dipole correctors activated**
  - **Kicks have fourfold ring symmetry as displaced quadrupoles move around the ring**
- **Can set up a matrix of kick sizes for each quadrupole displacement error**
  - **Multiplication of matrix times vector of arbitrary displacements gives correction for those displacements**
  - **Tested versus direct optimization for several sets of random errors, and agreement is good**



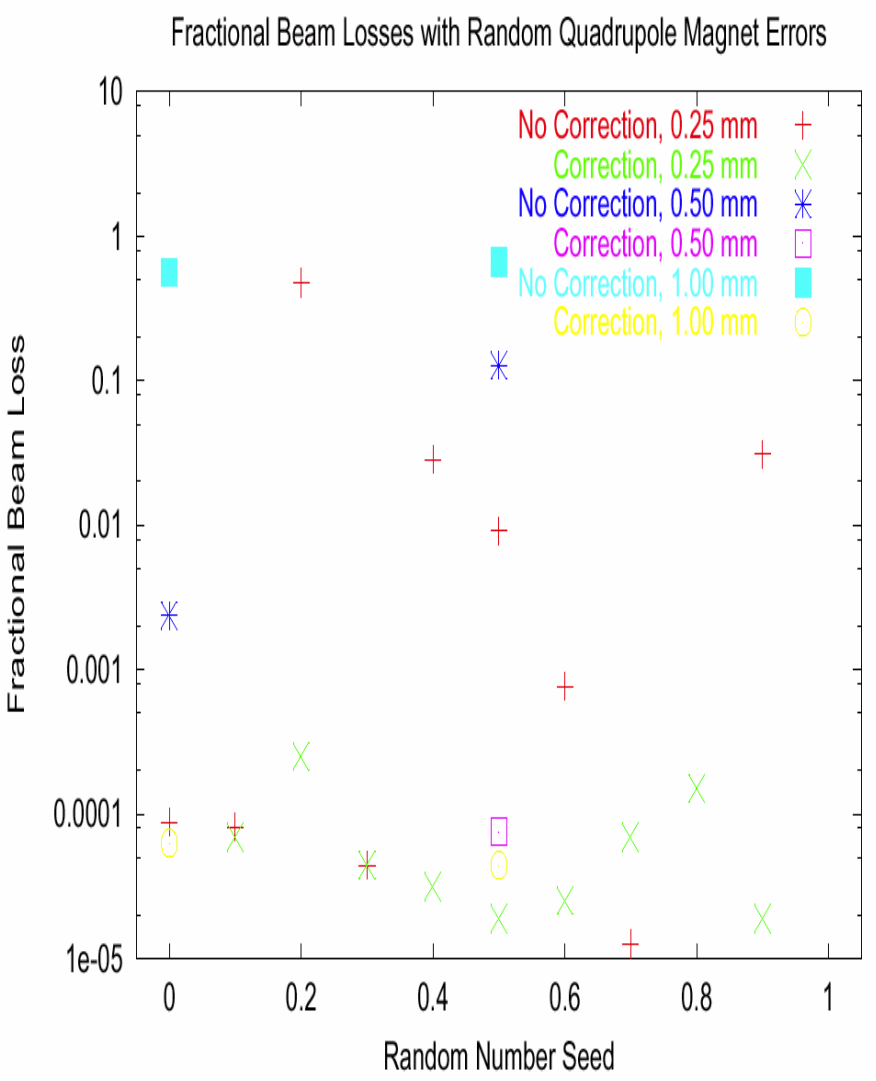
1 mm Single Quadrupole Displacement: Fractional Beam Loss at High Intensity

- For individual 1 mm quadrupole displacements, fractional beam losses vary from < 10^{-4} to > 10%, depending on location and lattice parameters at perturbed magnet.
- Losses are not periodic around the ring because apertures and collimation systems are not periodic.
- Correction of magnet errors reduces losses to ~ 10^{-4}



Random sets of quadrupole displacements: Fractional Beam Loss at High Intensity

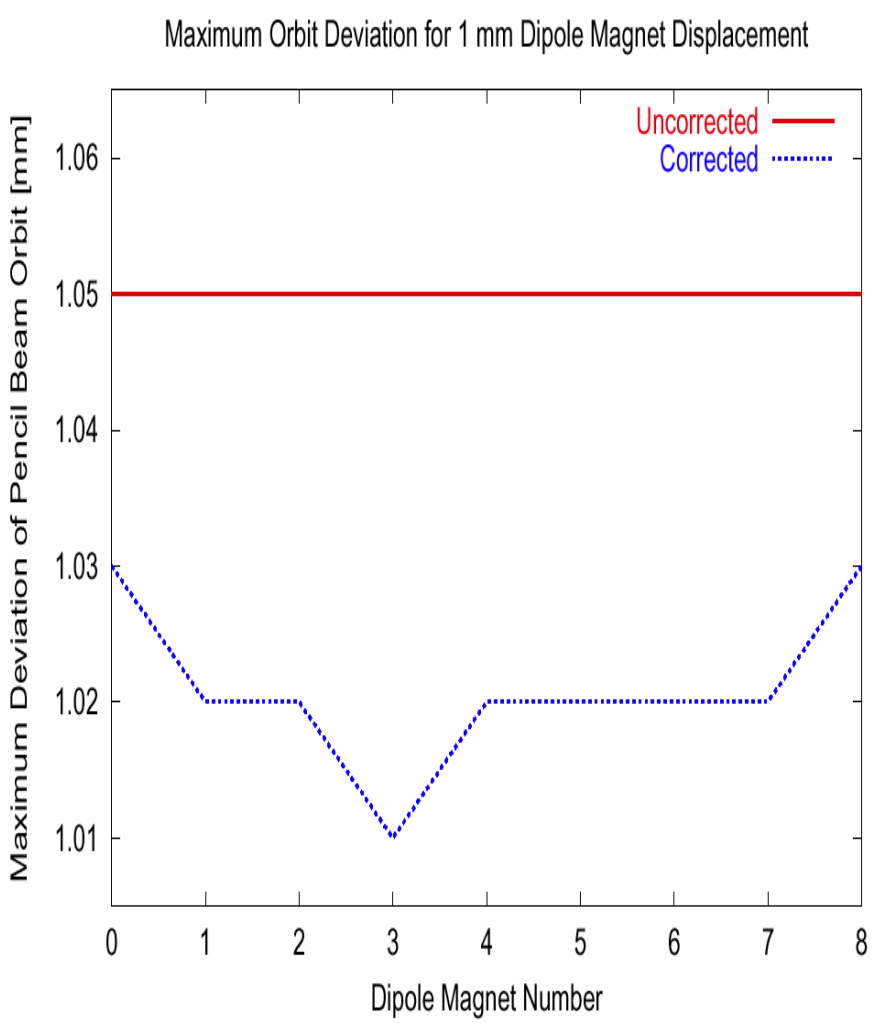
- **Random displacements assigned with uniform distribution $-a < D < a$. SNS specification is $a = 0.25$ mm.**
- **Several seed values and distribution limits for random errors tested. Uncorrected losses vary from 10^{-4} to substantial portions of the beam.**
- **Corrected beam losses always $< 3 * 10^{-4}$**

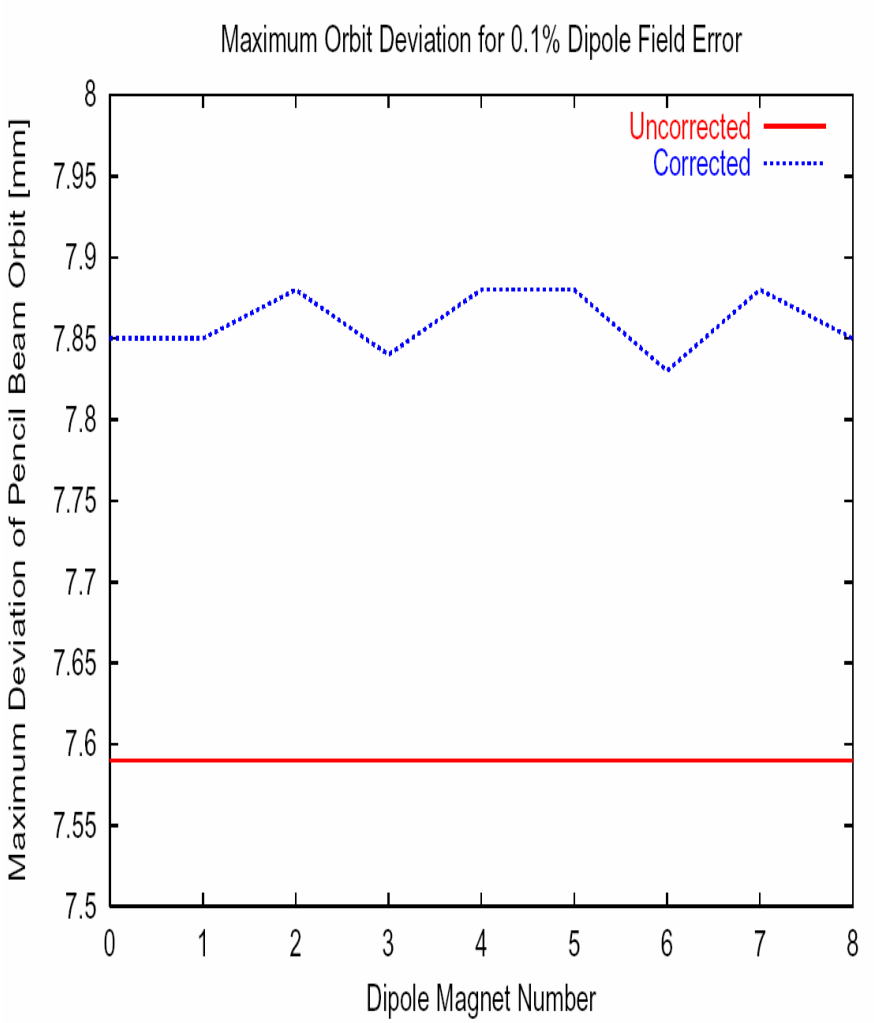


Dipole Displacement and Field Errors: Comparison With Quadrupole Errors

- Compared with quadrupole results:
  - 0.1% dipole field errors on individual magnets -> comparable orbit deviations to quadrupole displacements
  - 1 mm dipole displacement -> smaller orbit deviations than for quadrupole displacements
  - Correction doesn't reduce maximum deviations, but
  - 3 bump correction does localize orbit deviations between adjacent dipole corrector nodes
  - Dipole corrector kick strengths are smaller than those required for quadrupole displacement correction
  - As with quadrupole displacement errors, both orbit deviations and kicks have the fourfold SNS superperiodicity
  - For high intensity injection and no beam correction, losses were miniscule ($< 10^{-4}$) in all cases
    - Individual 1 mm displacements and 0.1% field errors
    - Random sets of 0.25 mm and 0.1% field errors with various seeds
    - Thus, correction of dipole errors at anticipated levels does not appear necessary

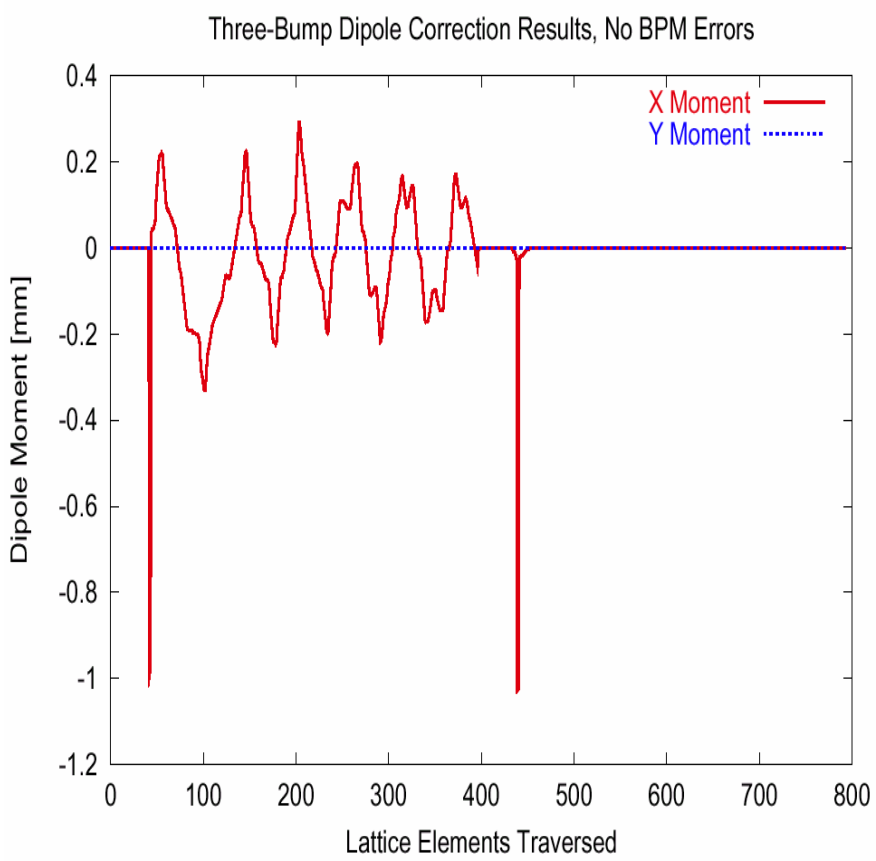
Individual Dipole Displacement and Field Errors: Maximum Orbit Displacements



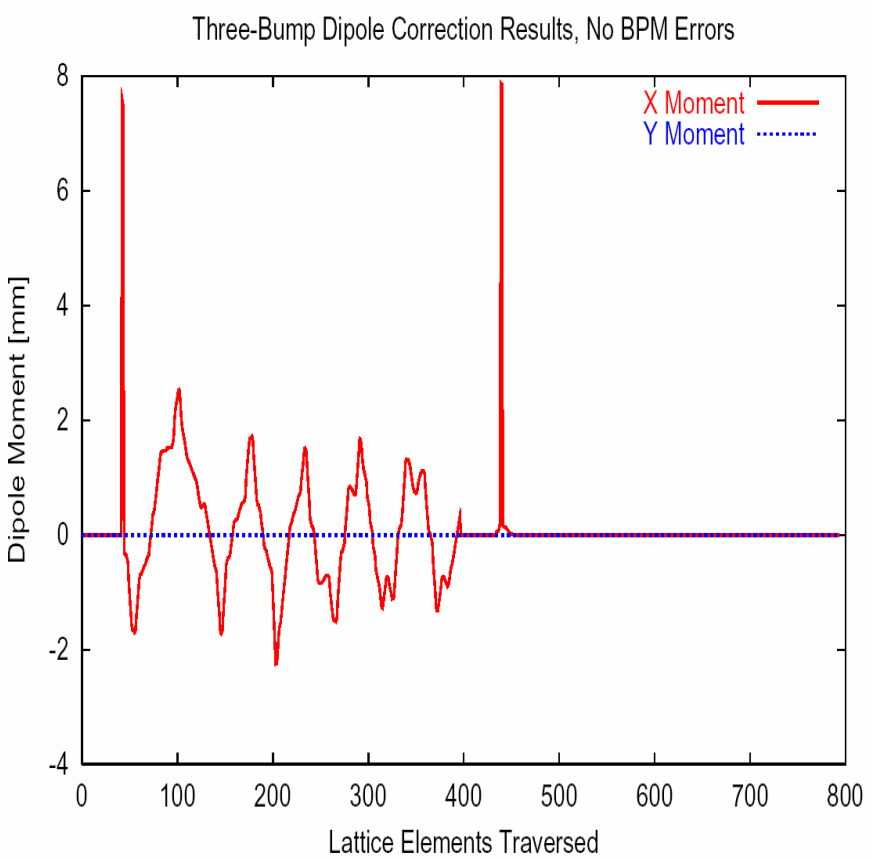


Maximum Orbit Deviations Are Small, Correction Doesn't Reduce Them

Individual Dipole Displacement and Field Errors: Maximum Orbit Displacements



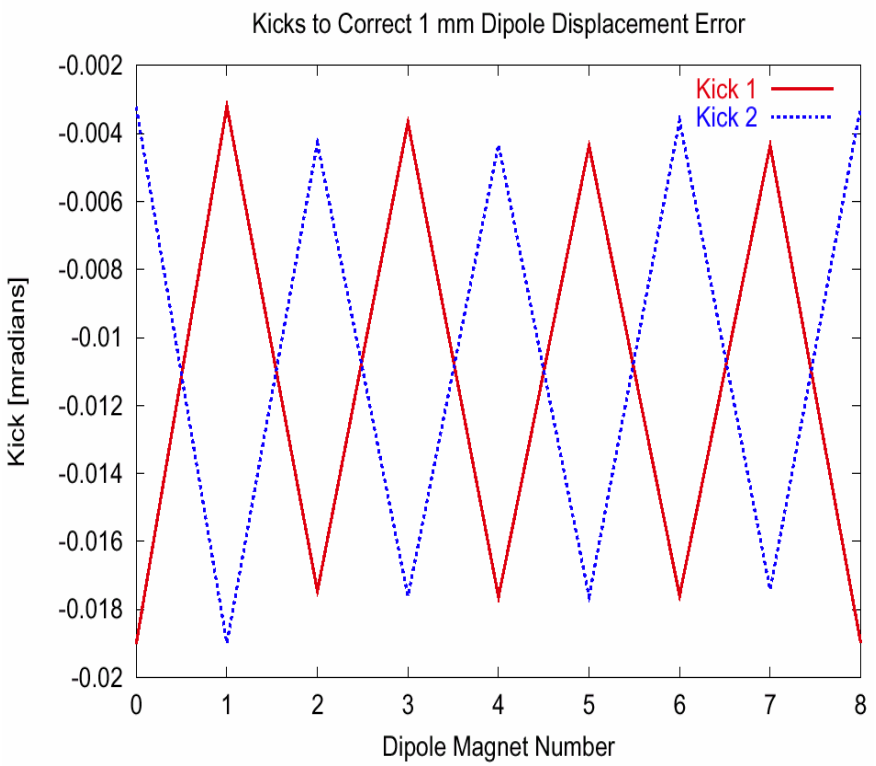
1 mm Dipole Displacement Error

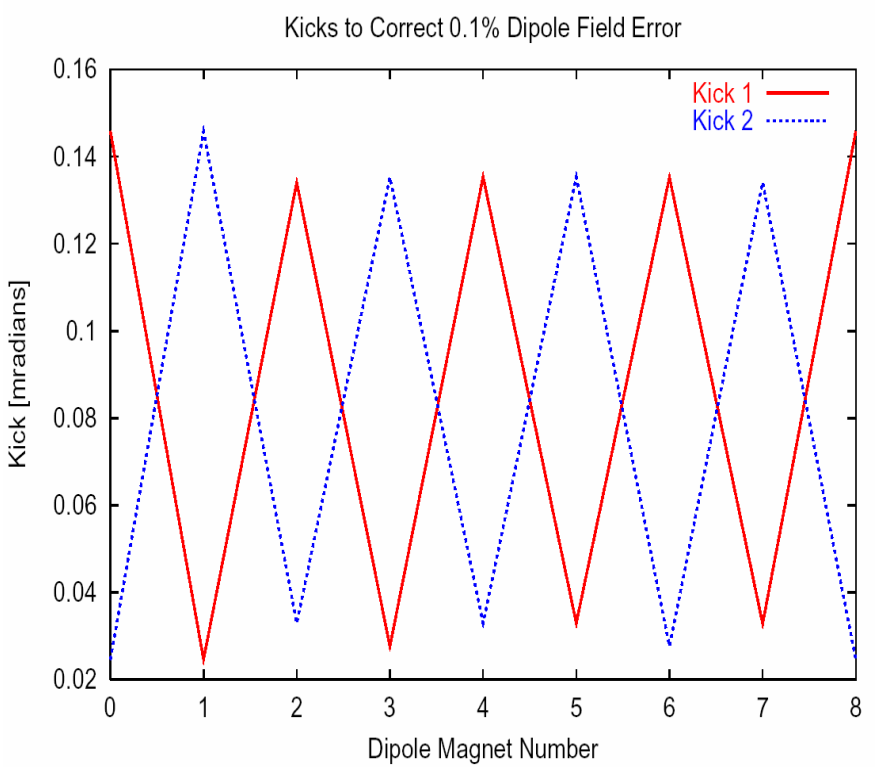


1 % Dipole Field Error

1 Turn Uncorrected Followed by 1 Turn Corrected, Exact BPM Signal

Individual Dipole Displacement and Field Errors: Dipole Corrector Kicks





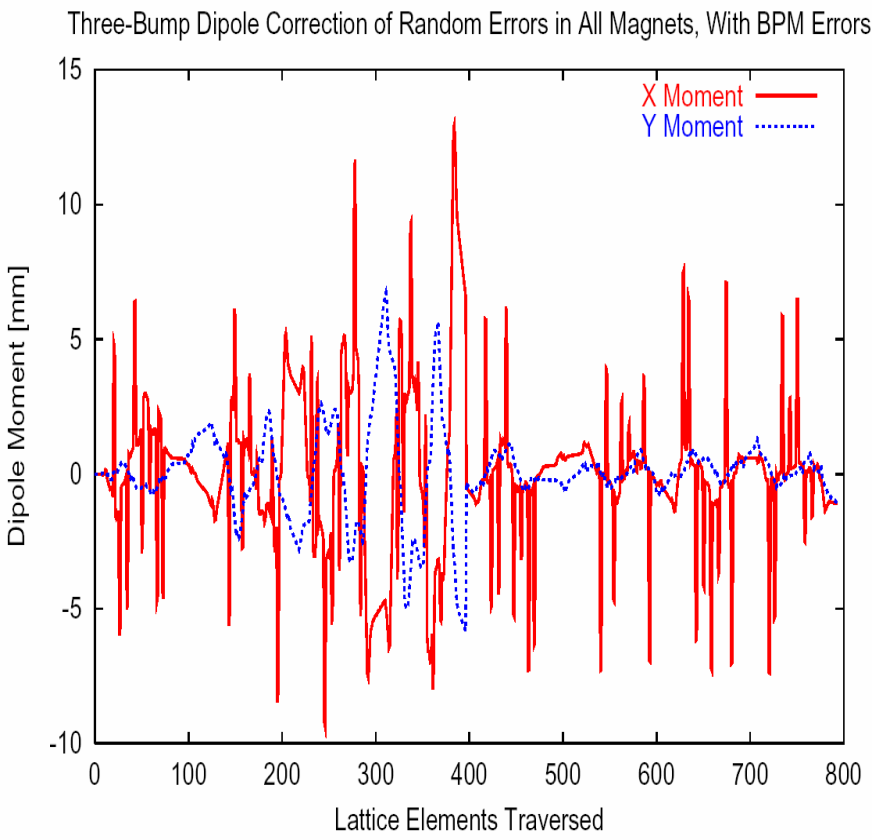
1 mm Dipole Displacement Error

1 % Dipole Field Error

Dipole Corrector Kick Sizes Are Small and Show Ring Superperiodicity

Worst Case Calculation With All 3 Errors

- Calculations were carried out with simultaneous activation of random sets of all 3 types of errors:
  - SNS tolerances were used
    - 0.25 mm for all displacement errors
    - 0.1% for dipole field errors
  - Random seeds were varied to find some bad loss cases
  - Correction was applied to the worst case
    - Both exact BPM signals and BPM signal errors were considered



1 Turn Before and 1 Turn After Correction Using BPM Signals With Errors

Worst Case Calculation With All 3 Errors: Beam Losses

- High intensity injection was calculated for the worst case:
  - Without correction, about 20% the beam was lost
  - With correction assuming exact BPM signals, < $2*10^{-4}$ was lost
  - With correction assuming BPM signal errors, < $3*10^{-4}$ was lost

- We conclude that the SNS ring orbit correction system using 52 BPM signals to optimize 52 dipole corrector strengths is adequate to correct orbit deviations due to quadrupole displacement errors, dipole displacement errors, and dipole field errors at the anticipated levels.